*A Distributed, Wireless MEMS Technology for Condition Based Maintenance**

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Abstract: Distributed MEMS networks can revolutionize critical military, industrial, and civil surveillance, transportation, manufacturing, and environmental management systems. Low cost sensor network development, coupled with the high performance of compact computing systems can provide new monitoring and control capability. Embedded microsensors and microactuators may provide control for improved dynamical response of large structures, for reduced requirements on dimensional precision, and for health monitoring and failure prediction of airframes, powerplants, buildings, and other structures. The installation of wireline networks for sensors raises important questions for condition based maintenance (CBM) system cost. For example, the installation of sensor network cables may require major modification to capitol equipment and vehicle systems, particularly for rotating component diagnostics. Thus, the development of autonomous, low power, wireless microsensors offers an opportunity to provide CBM at low cost to a wide range of applications. This presentation will describe fully integrated, wireless MEMS devices implemented with new RF communication and MEMS integration methods.

Key Words: Condition Based Maintenance, MEMS, wireless microsensors, low power electronics, infrared, vibration, and acoustic sensors.

Introduction: New product opportunities and new system capabilities are enabled by the development of a low cost distributed Microelectromechanical Systems (MEMS) technology. The development and deployment of distributed monitoring and controls has been hindered in the past by the requirements of complex installation and communication network requirements. Conventional distributed sensors have required cable interface, and therefore, extensive modification to structures and capitol equipment for their installation. The applications of distributed MEMS are being expanded by a new technology, Low Power Wireless Integrated Microsensors (LWIM). A wireless microsensor network may be distributed rapidly and without modification to large systems. In particular, LWIM nodes may be applied to rotating machinery without the complex slip-ring systems that would normally be required for a sensor electrical interface. In this paper the unique requirements and solutions emerging for wireless microsensor based CBM will be described.

A set of unique requirements exist for distributed wireless microsensor networks. The individual low cost sensor nodes must be 1) reconfigurable by their base station, 2) autonomous to permit local control of operation and power management, 3) self-monitoring for reliability, 3) power

efficient for long term operation. In addition, sensor nodes must incorporate diverse sensor capability with highly capable microelectronics.

LWIM intelligent node technology, based on commercial, low cost CMOS fabrication and bulk micromachining, has demonstrated capability for multiple sensors, electronic interfaces, control, and communication on a single device. LWIM nodes are fabricated by the new CMOS Integrated MicroSystems (CIMS) process. CIMS provides high sensitivity devices for vibration, acoustic signals, infrared radiation and other diverse signal sources. The central challenges for low cost, manufacturable, LWIM devices are the requirements for micropower operation and the complete integration of a CMOS RF transceiver. The CIMS process, micropower measurement, and micropower RF communication systems are described below.

Low Power Wireless Integrated Microsensors: A wireless microsensor technology has been developed that combines new micromachining methods with commercial CMOS to provide high performance, diverse, sensor capability combined with an integrated wireless interface. Low power electronics enables self-powered, autonomous, nodes for mobile applications. Bidirectional communication permits remote programmability. Integrated digital control provides adaptability and scalability. Finally, digital control of each LWIM node enables power and health management. The network architecture described here is a simple star network with a single, powerful base station, supplied by utility power, and numerous distributed wireless microsensors. Network architecture and communication protocols are developed to exploit the asymmetry of distributed sensor communication. Specifically, most information flow is from the sensor nodes to the base station with drastically less flow in the form of commands to the sensor nodes from the base station.

Typical CBM applications may be optimally serviced by sensor networks having local signal processing by sensor nodes. Thus, individual nodes may propagate condition measurements periodically to the base station. Only upon an alarm condition will continuous data transmission be required. This method permits a base station to service a much larger network than would be possible for simple continuous communication with sensor node. Instead, periodic updates of the network base station, by distributed network sensor nodes permits detection of changes in system (machinery) operation. For example, individual sensor nodes may provide continuous *measurement* of a vibration spectrum, while only *transmitting* the observation of a *change* in this spectrum. By exploiting the low duty cycle requirements for sensor communication, large efficiencies may be obtained in sensor node and base station operation. The remote programmability (enabled by including transmit and receive capability at each node) permits high data rate operation at any time that a request is made by the base station.

Completely independent LWIM nodes must operate at micro-ampere current levels and low voltage. This allows long operating life from compact battery systems. Alternatively, for some CBM applications, with nodes mounted directly on a motor or drivetrain shaft, LWIM nodes may receive power by continuous or periodic reception of RF energy from a nearby power source via an inductive coupling. Typical low duty cycle, low data rate (10kbps) and short range (10 - 30m) communication permit 30 μA average current for an LWIM node operating at 3V. A conventional Li coin cell provides this current level for greater than a three-year unattended operating life.

LWIM Node Fabrication Technology: The capability and flexibility required for LWIM intelli-

differs from previous systems in that analog sampling of the regenerative wave form (controlled by digital systems) is employed to provide demodulation. Thus, stable operation through automatic gain control is now possible. Current prototypes of this new receiver operate with sampling clock rates as high as 1MHz. Thus, receiver bit rate capability greater than 100kbps is permitted. Prototype LWIM nodes operating with 1mV transmitter power, and 10m range, require single loop antenna of less than $1cm^2$ area.

Summary: The wide range of Condition Based Maintenance (CBM) applications requires sensors carrying diverse measurement capability and network distribution capability. The prohibitive cost of connectors, cables, cable installation, and powerplant, vehicle, and structure modification creates the requirements for wireless sensor networks. A low power integrated wireless microsensor (LWIM) technology has been developed using new processes, circuits, and communication systems. Both RF induction and battery powered nodes may be implemented with the micropower system demonstrated here. LWIM nodes are under development for military and commercial CBM applications.

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gent nodes demands that LWIM microsensor systems employ conventional commercial CMOS technology. CMOS technology now provides the embedded control and micropower digital systems needed for LWIM nodes. Challenges remain for low noise, micropower analog measurement and RF communication systems. Demonstrated micropower CMOS measurement systems[1] for MEMS devices will be described below. The first integrated wireless microsensors have been implemented with the CMOS Integrated MicroSensors (CIMS) method. CIMS provides devices ranging from inertial to infrared,[2] and acoustic sensors in the same process (Figures 1, 2 and 3). CIMS combines commercial CMOS (post-processed after foundry-fabrication by XeF_2 micromachining)[3] with high performance bulk micromachined sensor and actuator structures (Figure 2 and 3) by flip chip bonding.

The CIMS process offer several advances over previous techniques. First, by separating the CMOS and bulk micromachining processes, conventional low cost CMOS technology may be directly applied. This offers the system developer great flexibility and the capability to update the circuit technology rapidly as progress continues in this rapidly changing area. In addition, the separation of CMOS and sensor element fabrication permits the introduction of novel materials, for example pyroelectric systems,[2] without disturbing critical CMOS processing.

CIMS also offers performance advantages for CBM sensors. Specifically, the use of bulk micromachined structures enables large proof mass values for inertial and vibration sensors. Single crystal flexures provide stability. Finally, the long standing problem of parasitic capacitance is directly addressed by a unique suspended electrode structure (Figures 1 and 2). The suspended electrode eliminates the need for Si-on-glass for many applications. Also, the proper design of the suspended electrode permits control of squeeze-film damping.

The acceleration and infrared sensors, implemented by the CIMS process, are shown in Figures 1, 2, and 3. Figure 1 displays the CMOS interface die component of the CIMS process. The interface die contains low parasitic capacitance measurement, data conversion and RF communication capability. The CIMS accelerometer relies on a single crystal flexure supporting a proof mass with a resonance frequency that may be adjusted (by design) from 10kHz to 100Hz. The CIMS infrared sensor relies on a new silicon-compatible $PbTiO_3$ sol-gel material system that is applied to the CIMS sensor die in a modular process separated from CMOS fabrication.[2] Direct measurement (Figure 3) yields a responsivity of 4V/Watt for this pyroelectric sensor. Integrated measurement systems, with micropower operational amplifiers and data conversion systems (Figure 4) provide switched-capacitor measurement capability for CIMS devices.

LWIM Systems and Wireless Communication: The wireless sensor technology reported here differs from prior work in that the sensor, control, and communication system are *integrated together in a single unit.* In addition, we have addressed the challenge of combining low noise, high performance measurement and data conversion sensor interfaces with micropower operation in CMOS systems. An important technology challenge is the development of micropower, integrated CMOS RF systems. This requires advances in both level of integration, sharp reduction in operating power, and a conversion from conventional bipolar technology to CMOS.

A new micropower communication system has been demonstrated based on the first CMOS, surface acoustic wave (SAW) stabilized receivers and transmitters (Figure 4). These high selectivity micropower receiver systems have been operated at 320MHz with detector currents of less than 30 μA at 3V supply bias. This device relies on the regenerative receiver principle. However, it

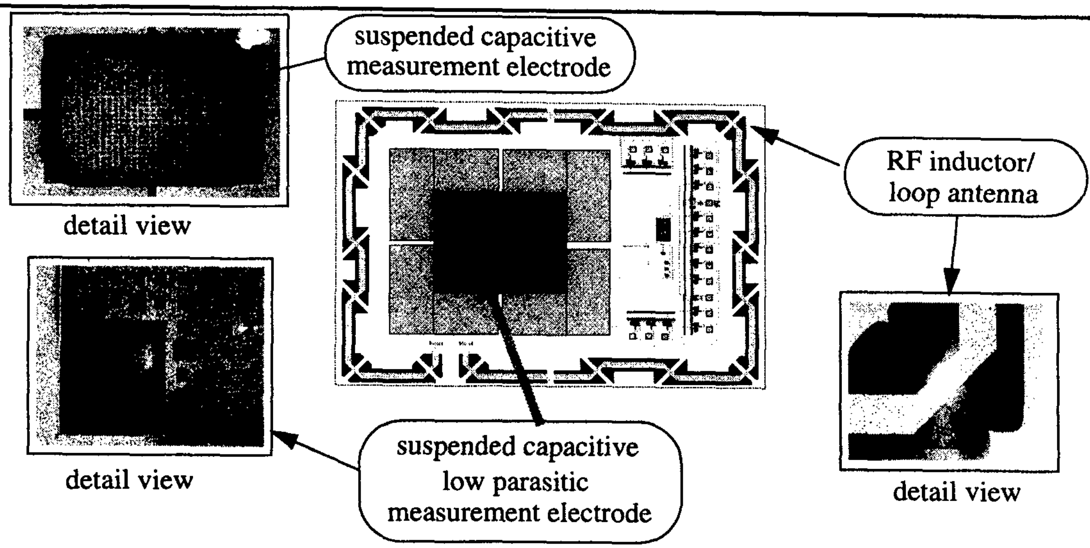


Figure 1. **Wireless Microsensor Interface Die.** The Interface Die provides sensor measurement, sensor interface, control, and RF communication functions in a single integrated component. The Interface Die, fabricated in commercial 2.0µ CMOS, is integrated with high performance sensor elements by flip chip bonding. These micrographs display the low parasitic capacitance, suspended measurement electrodes, and suspended inductor / loop antenna. The CMOS die was processed after fabrication by a mask-less etch in XeF_2.

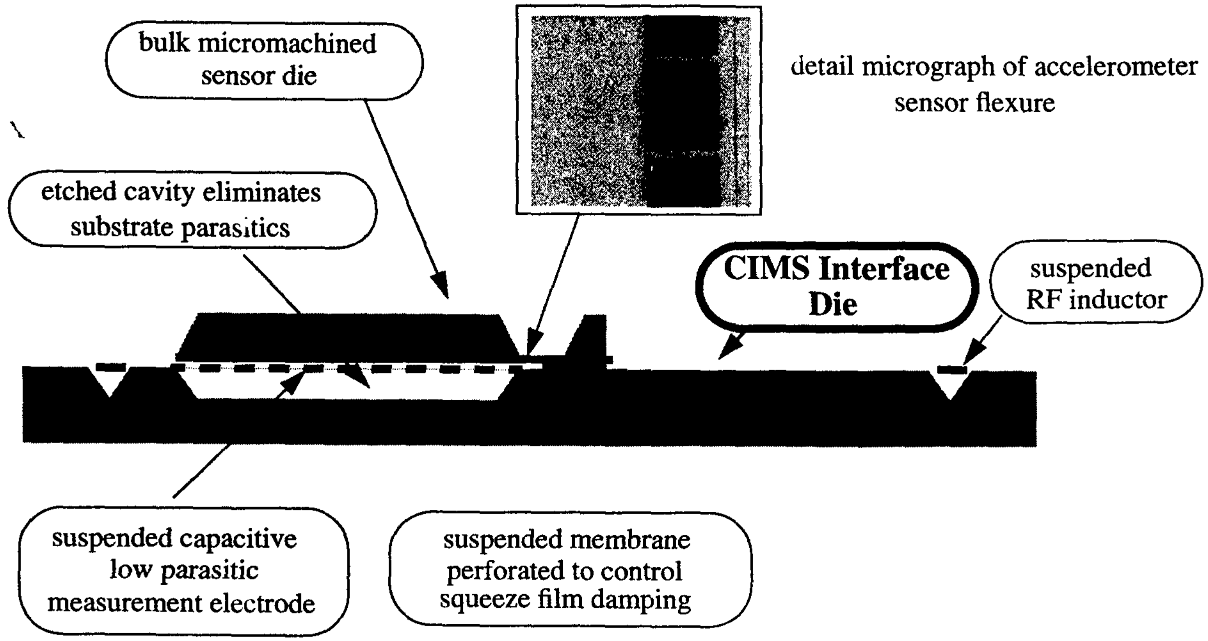
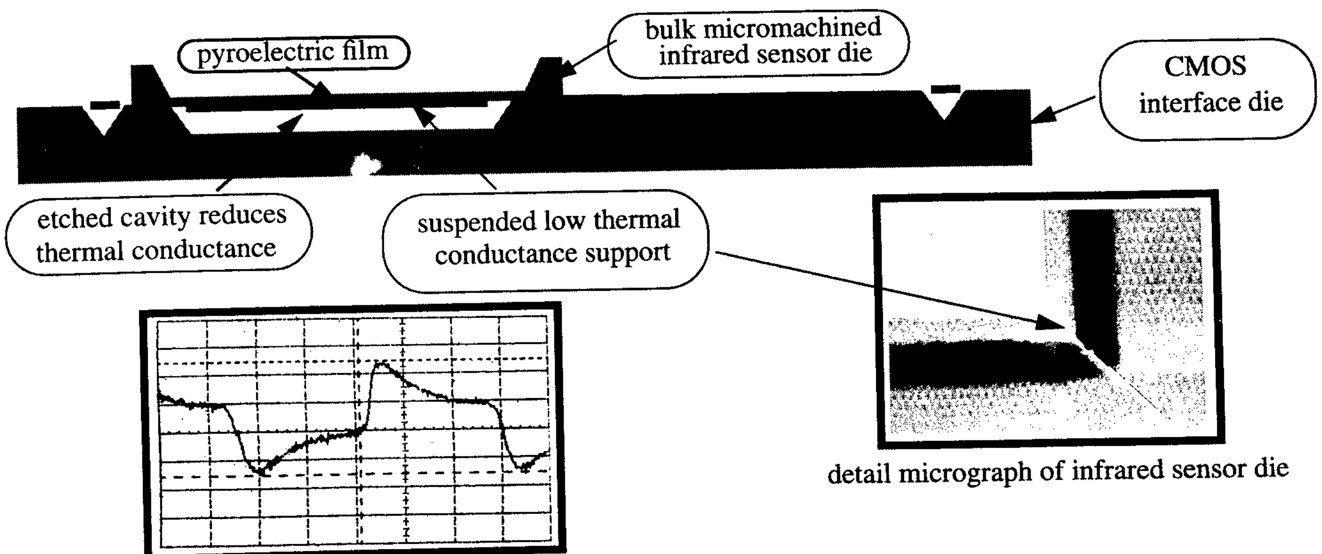


Figure 2. **Wireless Accelerometer Cross-Section.** The accelerometer employs capacitive sensing with a suspended measurement electrode. A micromachined cavity drastically reduces substrate parasitics that limit conventional devices. Membrane perforation provide control of squeeze film damping without requirements to perforate the proof mass.



Infrared sensor response - 80 mV peak-peak output signal for
20 mW peak-peak incident infrared signal *measured at transducer*

Figure 3. **Wireless Infrared Sensor Schematic Cross-Section.** The wireless infrared sensor employs a low thermal conductance structure supporting a sol-gel thin film pyroelectric infrared sensor. Flip chip bonding of sensor to interface die permits separation of the high temperature, ideal infrared material processing, from commercial CMOS fabrication.

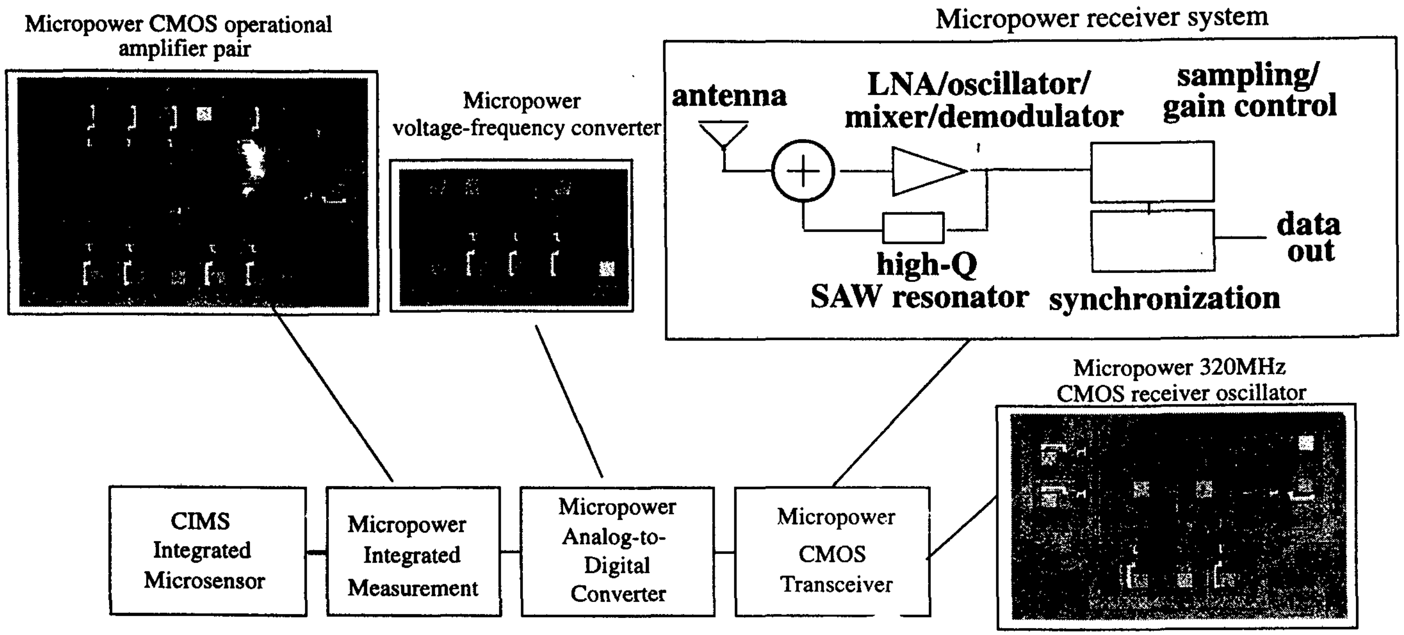


Figure 4. **Wireless Integrated Sensor System.** Measurement, data conversion, and communication systems have been demonstrated in commercial 2µ CMOS. A micropower operational amplifier (supply current 1µA) is combined with micropower voltage-frequency data converters (supply current 2µA). The transceiver is based on a low power CMOS, SAW stabilized and digitally-sampled regenerative architecture (peak supply current 30µA).